WJEC (Eduqas) Physics A-level

Topic 3.9: Magnetic Fields

Notes

B - Fields

A magnetic field, also known as a B-field, is a field that exerts a force on magnetized materials, moving charges and electrical currents (e.g a current carrying wire).

When a current carrying wire is placed in a magnetic field, a force is exerted upon it, and we can determine the direction of this force using **Fleming's left hand rule** which is illustrated as follows:

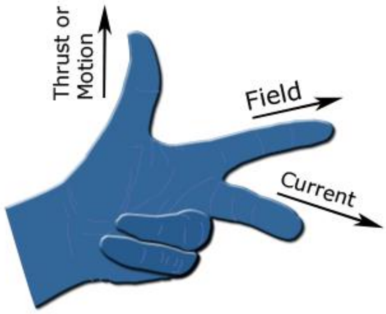

Image source: By Douglas Morrison DougM - en.wiki, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=986716

Which shows how the **force on the wire is always perpendicular to the direction of the B-field and the direction of the (conventional) current.** A useful way to remember this is pretending your hand is a gun and saying 'FBI' (force, B-field, current) to yourself, remembering to go from the thumb to the middle finger.

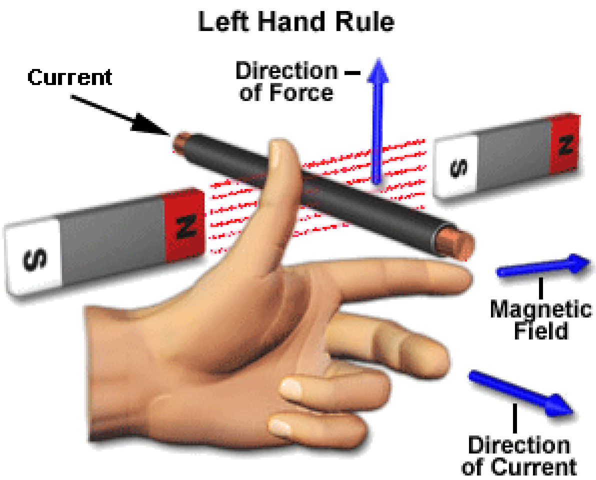

Image source: https://www.electrical4u.com/fleming-left-hand-rule-and-fleming-right-hand-rule/

In the image above the wire experiences a force pushing it upwards.

We can use this fact to calculate the magnetic flux density B acting on the wire using the following equation (provided in the equation sheet):

$$F = BILsin(\theta)$$

Where F is the force exerted on the wire by the B-field, I is the current flowing through the wire, L is the length of the wire and θ is the angle between the B-field and the direction of the current. From this we see that:

$$B = \frac{F}{ILsin(\theta)}$$

The unit of B is the **Tesla** which is defined as the field strength that causes a wire carrying a current of 1A to experience a force of 1N per 1 metre. In the case of the direction of the current being perpendicular to the magnetic field the above equation simplifies to

$$B = \frac{F}{IL}$$

Since sin(90)=1.

Since magnetic fields exert a force on moving charges, we can derive a formula for this by considering a charge q moving through a magnetic field B. If the charge is moving at a constant velocity v it is creating a current (since it is a moving charge), and this current moves a distance l in a time t. So,

$$v = \frac{l}{t}$$

$$l = vt$$

And since we have a current equal to q/t and by the formula above the force on a current carrying section is:

$$F = BILsin(\theta)$$

We get:

$$F = B(\frac{q}{t})(vt)sin(\theta)$$

$$\Rightarrow \ F = Bqvsin(\theta)$$

Which is the formula for the force on a moving charge. Since the **force is always perpendicular** to the moving charge we get that the charge will be made to **travel in a circle** since it has a constant centripetal force acting on it.

We can use Fleming's left hand rule to work out the direction of this force - just watch out for **negative charges as they will reverse the direction of the middle finger**!

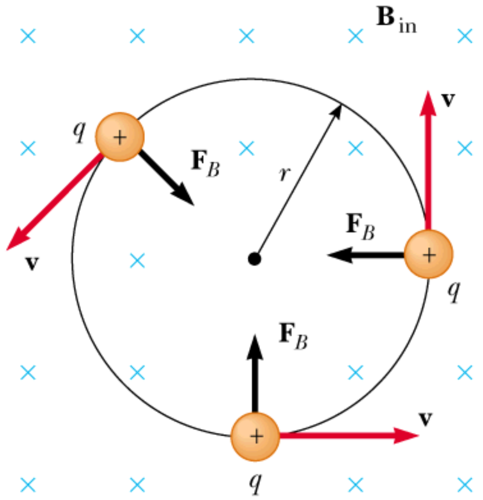

Image source: https://physexams.com/blog/Motion-of-a-charged-particle-in-a-uniform-magnetic-field_13

Since the force gives rise to circular motion, we can equate the formula for force and centripetal force for a charged particle moving at a constant velocity perpendicular to a magnetic field:

$$F = Bqv = \frac{mv^2}{r}$$

$$Bq = \frac{mv}{r}$$

And in particular, we can calculate the radius of the circular motion:

$$\underline{r = \frac{mv}{Bq}}$$

Hall Voltage

When a magnetic field is applied across a current carrying conductor, the **electrons inside experience a force** and are pushed to one side. The angle between the direction the electrons are travelling and the B-field is 90 degrees.

Since the electrons will be on one side of the material, we get a **potential difference across the material** which is known as the **Hall voltage**, V_H. We also get an **electric field acting in the opposite direction** caused by the building up of negative charge on one side.

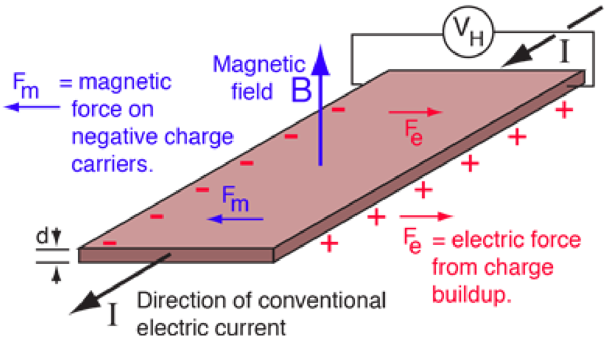

Image source: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/Hall.html

We know that the electric field strength is given by

$$E = \frac{V_H}{d}$$

Where d is the width of the conductor. This E-field will also cause a force on the electrons which is given by

$$F = Eq$$

Where q is the electron's charge. Combining the equation for E and F gives us that

$$F = \frac{V_H}{d}q.$$

Now, this **force will repel electrons** being pushed to the negatively charged side of the conductor by the B-field. This means that once the electric and magnetic force are equal, the flow of electrons will stop:

$$Bqv = \frac{V_H}{d}q$$

$$Bv = \frac{V_H}{d}$$

Now, we can use the equation that relates current to the electron drift velocity from a previous topic, $I = nAve$, where n is the electron dentistry of the conductor, $A$is the cross sectional area v is the drift velocity and e is the electrons charger. Rearranging for v and substituting into the above equation gives

$$B\frac{I}{nAe} = \frac{V_H}{d}$$

$$\Rightarrow V_H = B\frac{Id}{nAe}$$

Which shows how the **Hall voltage is proportional to** $B$for a fixed current.

Magnetic Fields due to Current Carrying Wires and Solenoids

A current carrying wire produces a magnetic field around it when current is flowing, the shape of which can be worked out using the curl right hand rule,seen in the figure below.

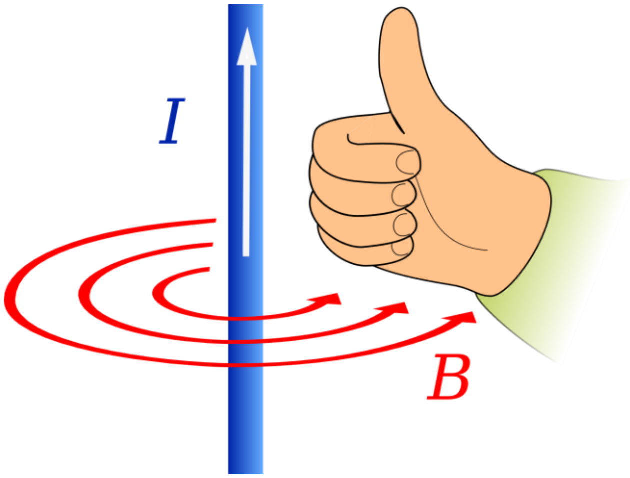

Image source: By Jfmelero - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=3634402

Simply point your thumb in the direction of the current and curl your fingers in towards your palm, this curl is the direction of the concentric circles that form the B-field.

We can also calculate the **magnetic field as a function of distance from the wire**, using the following equation found the in the equation booklet:

$$B=\frac{\mu_0 I}{2\pi x}$$

Where μ_0 is the permeability of free space($4\pi \times 10^{-7} Hm^{-1}$), I is the current and x is the radial distance from the wire. Where this equation comes from is too advanced for A-level but if you're interested check out the **Biot-Savart law**!

A solenoid is a coil of current carrying wire that creates an almost uniform magnetic field through the centre of the coil:

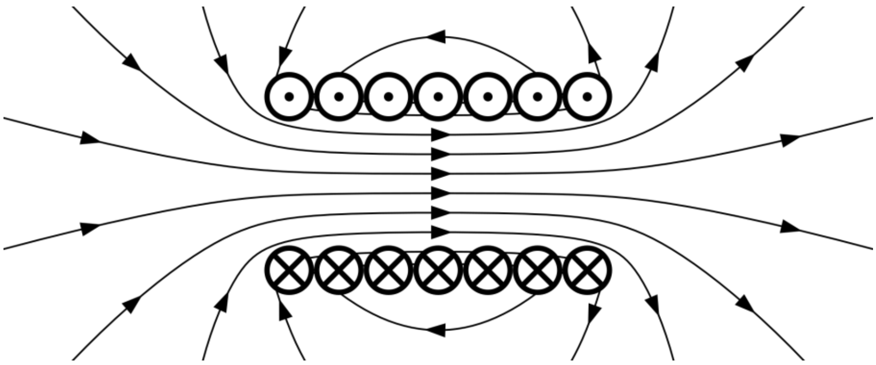

Image source: By Geek3 - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10618762

We can calculate the magnetic field of a solenoid using the following equation, which is also in the equation booklet:

$$B=\mu_0 nI$$

Where n is the number of turns of the wire around the solenoid per unit length and μ_0 and I are the same as before.

We can **increase the magnetic field strength by adding an iron core** inside the solenoid, since the iron core becomes magnetised so we get an additional magnetic field on top of the solenoid one.

Forces between current carrying wires

When we place two current carrying wires next to each other, they exert a force on each other.

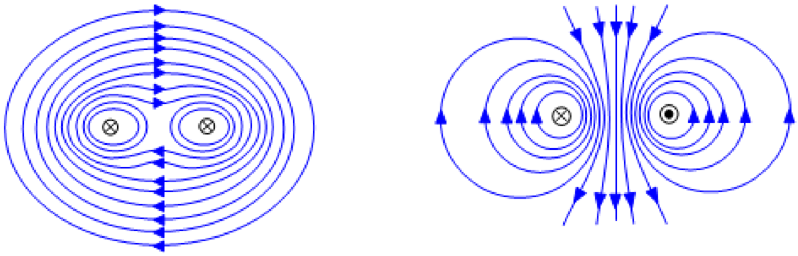

Image source: http://www.schoolphysics.co.uk/age16-19/Electricity%20and%20magnetism/Electromagnetism/text/Forces_between_currents/index.html

When the current is travelling in the **same direction, the wires attract each other** and when the current is travelling in the **opposite direction, the wires repel each other**. This can be seen by using Fleming's left hand rule.

Uniform Electric Fields

When a charged particle enters a **uniform electric field** at a **right angle**, it is deflected in a parabola and the force is given by:

$$F = Eq$$

Where E is the electric field strength and q is the charge of the particle.

If the electric field is **uniform between two charged plates** separated a distance d apart with a potential difference of V we can use the fact that $E = V/d$ to get:

$$F = \frac{Vq}{d}$$

And, by using Newton's second law $F = ma$ we get that (verticle) acceleration of the charged particle of a mass m is:

$$a = \frac{Vq}{md}$$

Particle accelerators

Linear Accelerators: Ions are accelerated using an **alternating p.d**. The **acceleration occurs between the drift tubes** (the grey tubes in the below figure). This is because as the voltage is alternating such that the electric field produced by the p.d is always accelerating the ion from left to right when it is in the gaps and when it is in adrift tube it is shielded from the portion of the E-field that would otherwise decelerate it.

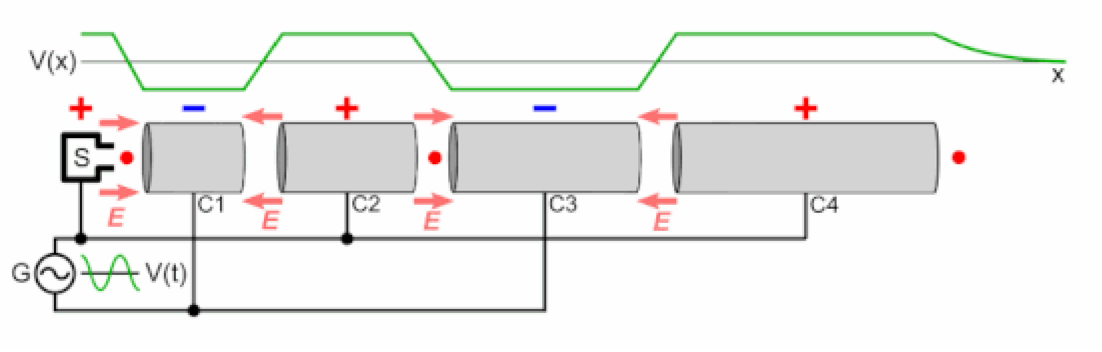

Image source: By Chetvorno - Own work, CC0, https://commons.wikimedia.org/w/index.php?curid=68477306

Cyclotrons: In a cyclotron, a uniform magnetic field keeps the ion in circular motion and, as can be seen in the below figure, an alternating electric field accelerates the ion as it passes over the gap in the middle.

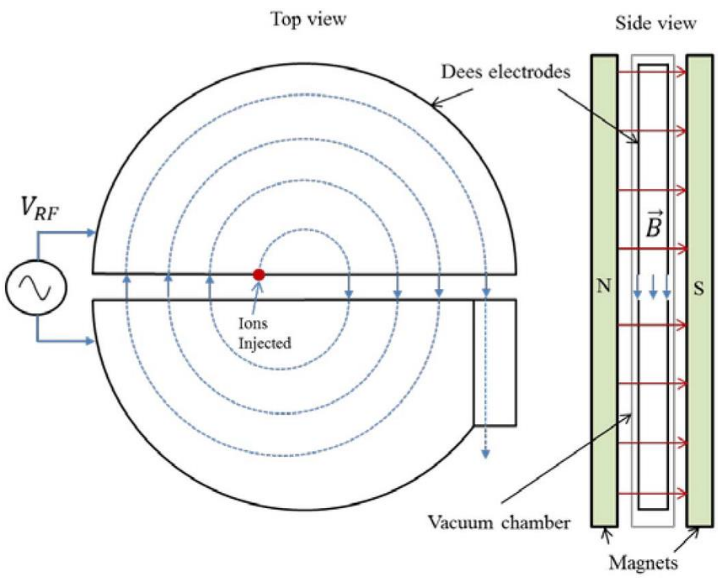

Image source: History and Technology Developments of Radio Frequency (RF) Systems for Particle Accelerators - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Schematic-view-of-the-classical-cyclotron-principle_fig21_283861027 [accessed 20 Nov, 2020]

The centripetal force from the B-field equated with the formula for centripetal force gives:

$$Bqv = \frac{mv^2}{r}$$

Where r is the radius of the path the ion is following. This shows how the **radius increases as v increases**.

And we can also relate the velocity of the ion with the frequency of the frequency of the A.C supply:

$$v = 2\pi rf$$

If the particle begins to move at a relativistic speed, the motion of the particle comes out of sync with the alternation of the E-field.

Synchrotrons: The synchrotron accelerates ions by passing them through **alternating electric fields** situated at intervals in the beam pipe. The **ions are kept in place by magnetic fields** that must alter as the ion's velocity increases. Unlike the cyclotron, the frequency of the alternating current can be altered/increased for higher velocities so **higher speeds can be reached** without relativistic effects becoming an issue.

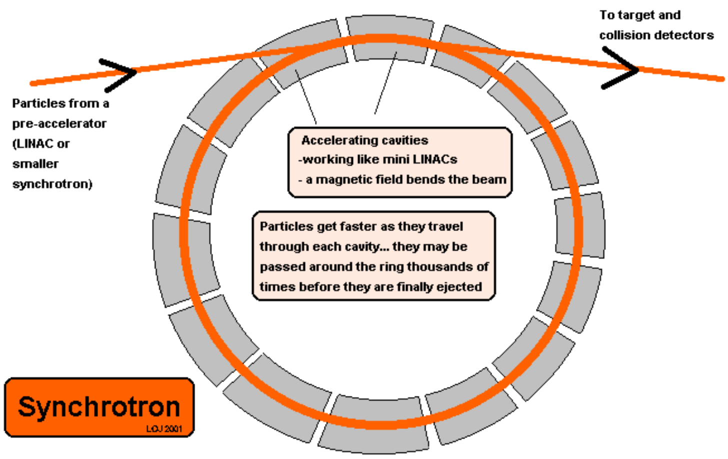

Image source: https://www.cyberphysics.co.uk/topics/atomic/Accelerators/Synchrotron/synchrotron.htm